A Beam Test of Prototype TPCs using Micro-Pattern Gas Detectors at KEK

An Interpretation of the Results
and
Extrapolation to the LC-TPC

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on behalf of part of
the ILC-TPC Collaboration

KEK, Saclay, Orsay, Carleton, Montreal, MPI, DESY, MSU、
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Outline

1. ~~Experiments and examples of the result~~
2. Analytic formulation of the spatial resolution (and pad response)
3. Comparison with the experimental results (preliminary)
4. Calculated spatial resolution of the LC TPC
5. Summary

ILC-TPC R&D Groups

Europe

RWTH Aachen
CERN
DESY
U Hamburg
U Freiburg
U Karlsruhe
UMM Krakow
Lund
MPI-Munich
NIKHEF
BINP Novosibirsk
LAL Orsay
IPN Orsay
U Rostock
CEA Saclay
PNPI StPetersburg

America

Carleton U
Cornell/Purdue
Indiana U
LBNL
MIT
U Montreal
U Victoria

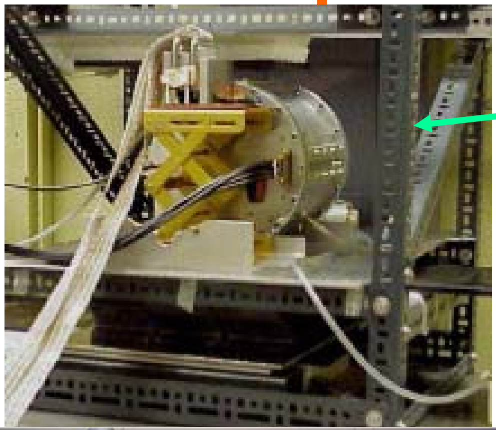
Asian ILC gaseous-tracking groups

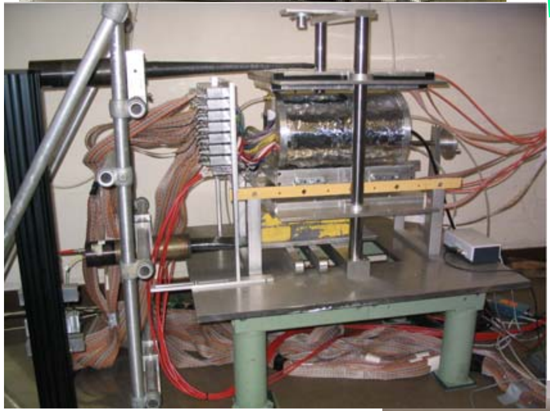
Chiba U
Hiroshima U
Minadamo SU-IIT
Kinki U
U Osaka
Saga U
Tokyo UAT
U Tokyo
NRICP Tokyo
Kogakuin U Tokyo
KEK Tsukuba
U Tsukuba
Tsinghua U

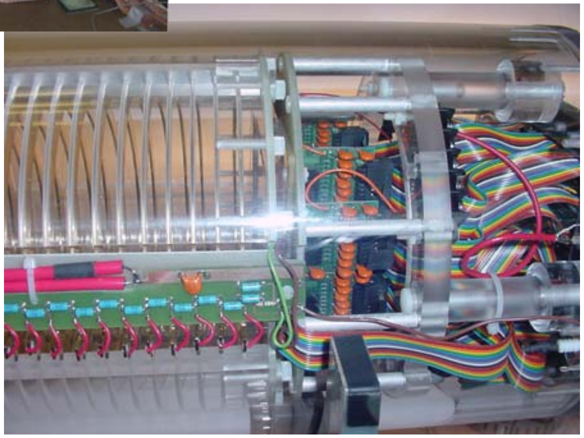
Other

MIT (LCRD)
Temple/Wayne State (UCLC)
Yale

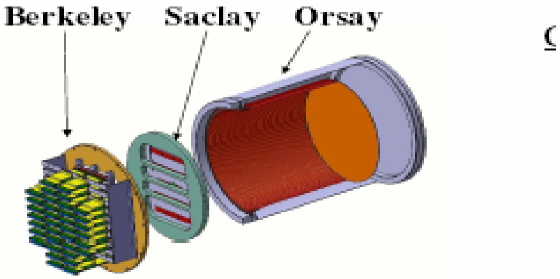
Examples of Prototype TPCs

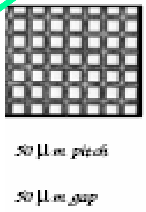


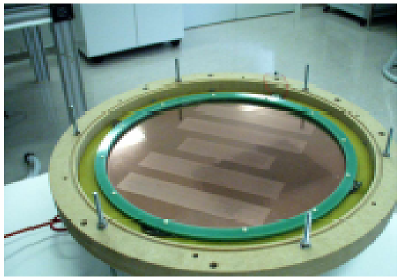




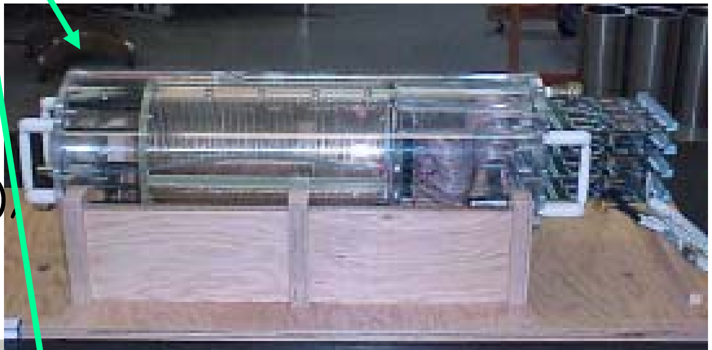
Carleton, Aachen,
Cornell/Purdue,Desy(n.s.)
for B=0or1T studies

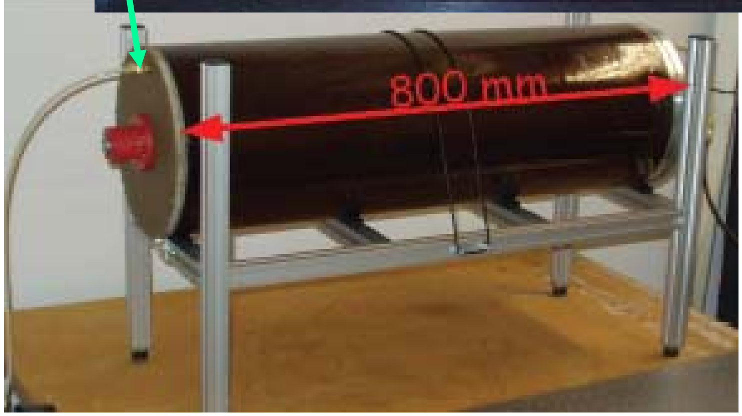






Saclay, Victoria, Desy
(fit in 2-5T magnets)





Karlsruhe, MPI/Asia,
Aachen built test TPCs
for magnets (not shown),
other groups built small
special-study chambers

ILC-TPC

A Large, High precision, High 3-D granularity Time Projection Chamber operated under a high magnetic field of 3 – 4 T

Size: Effective volume = 4.1 m (diameter) × 4.6 m (full length)

Spatial resolution

r-ϕ : 100 – 200 μm　　z: $\lesssim$ 1 mm

Two-track resolving power

r-ϕ : $\lesssim$ 2 mm　　z: $\lesssim$ 10 mm

Number of coordinate samples per track: ~ 250

Momentum resolution (TPC alone)

$\delta Pt / Pt \sim 10^{-4}$ Pt [GeV/c] for high momentum tracks

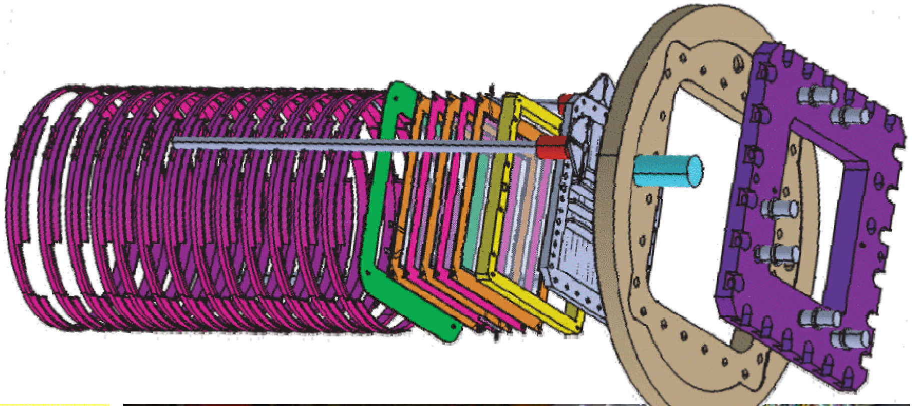
Particle identification capability: dE/dx ~ 4%

Unprecedented requirements to TPC especially for granularity

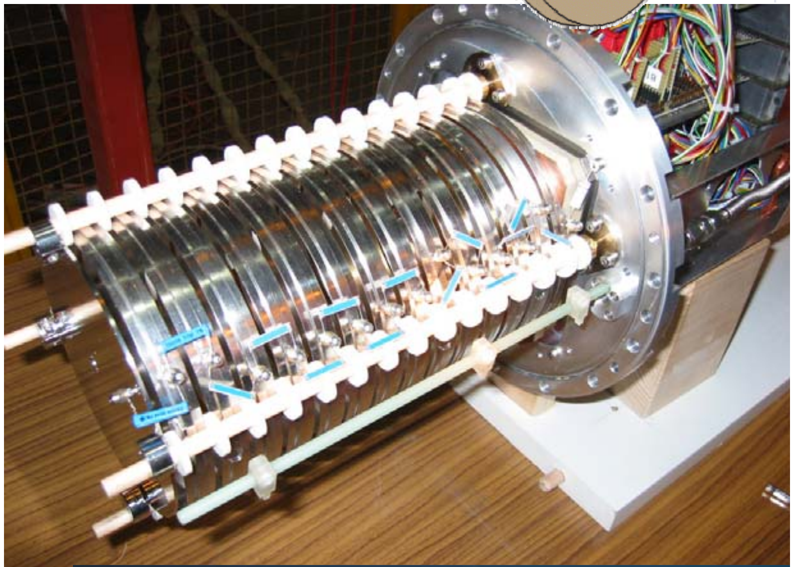
→ use of micro pattern gas detector (MPGD) as a readout device

→ performance tests using prototypes

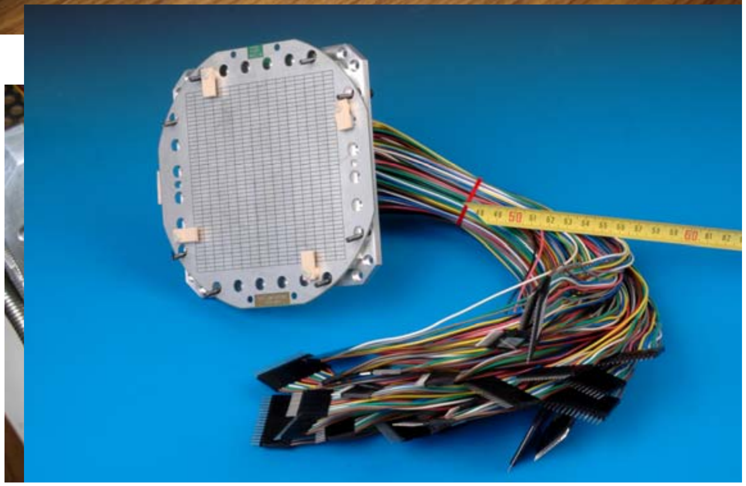
Prototype TPC



Field cage
- maximum drift length: 260 mm
- typical cathode H.V. : - 6 kV



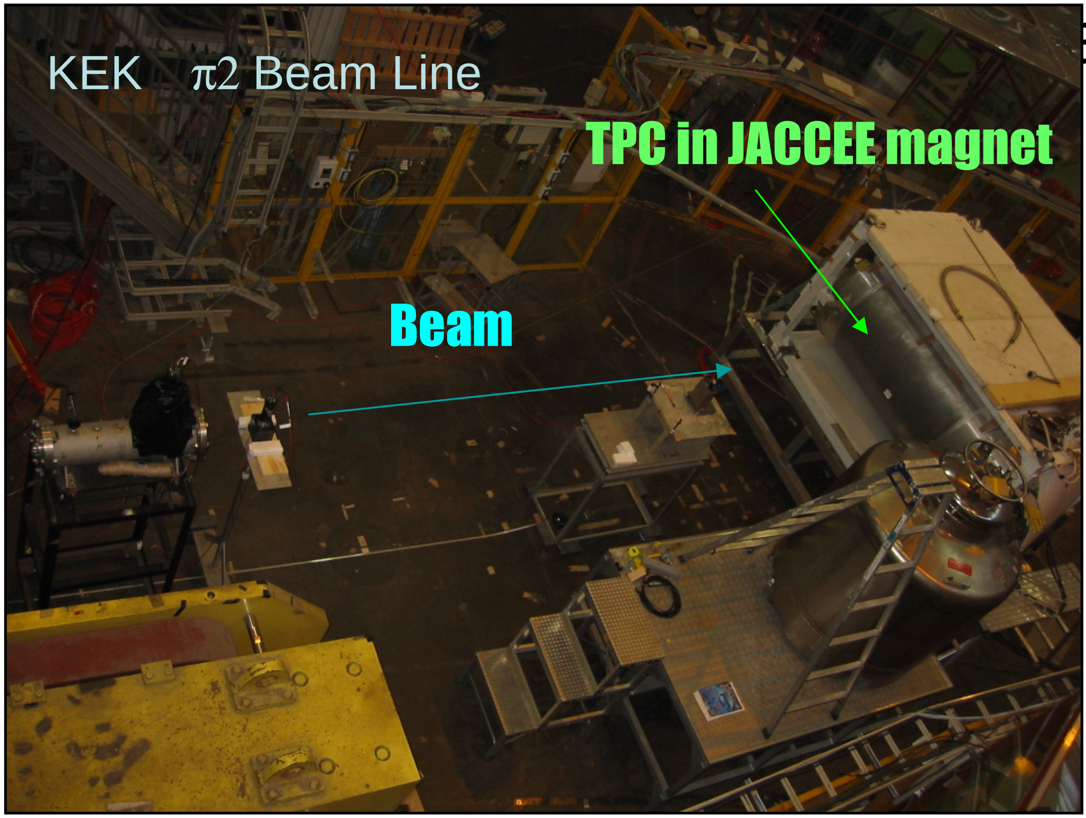
Readout plane
- effective area: 100 mm × 100 mm
  - MWPC
  - GEMs (3-stage)
  - or
  - MicroMEGAS



Experimental setup

We have conducted a series of beam experiments at KEK PS.

- **Beam**: mostly 4 GeV/c pions (0.5-4 GeV/c hadrons & electrons)
- **Magnet**: super conducting solenoid



JECCEE
inner diameter : 850 mm
effective length: 1 m

Readout scheme and Gas

Readout Device	Pads： 32 pads ×12 pad rows Width (pitch)×Length (pitch)	Gas (1 atm.) Drift field
MWPC SW spacing 2 mm SW - Pads 1 mm	2 (2.3) mm×6 (6.3) mm	TDR [Ar-CH$_4$ (5%)-CO$_2$ (2%)] 220 V/cm
GEM (triple stage) CERN Standard transfer gaps 1.5 mm induction gap 1.0 mm	1.17 (1.27) mm×6 (6.3) mm staggered	TDR 220 V/cm Ar – methane (5%) 100 V/cm
MicroMEGAS 50-μm mesh 50-μm gap	2 (2.3) mm×6 (6.3) mm	Ar - isobutane (5%) 220 V/cm

ALEPH TPC Electronics：

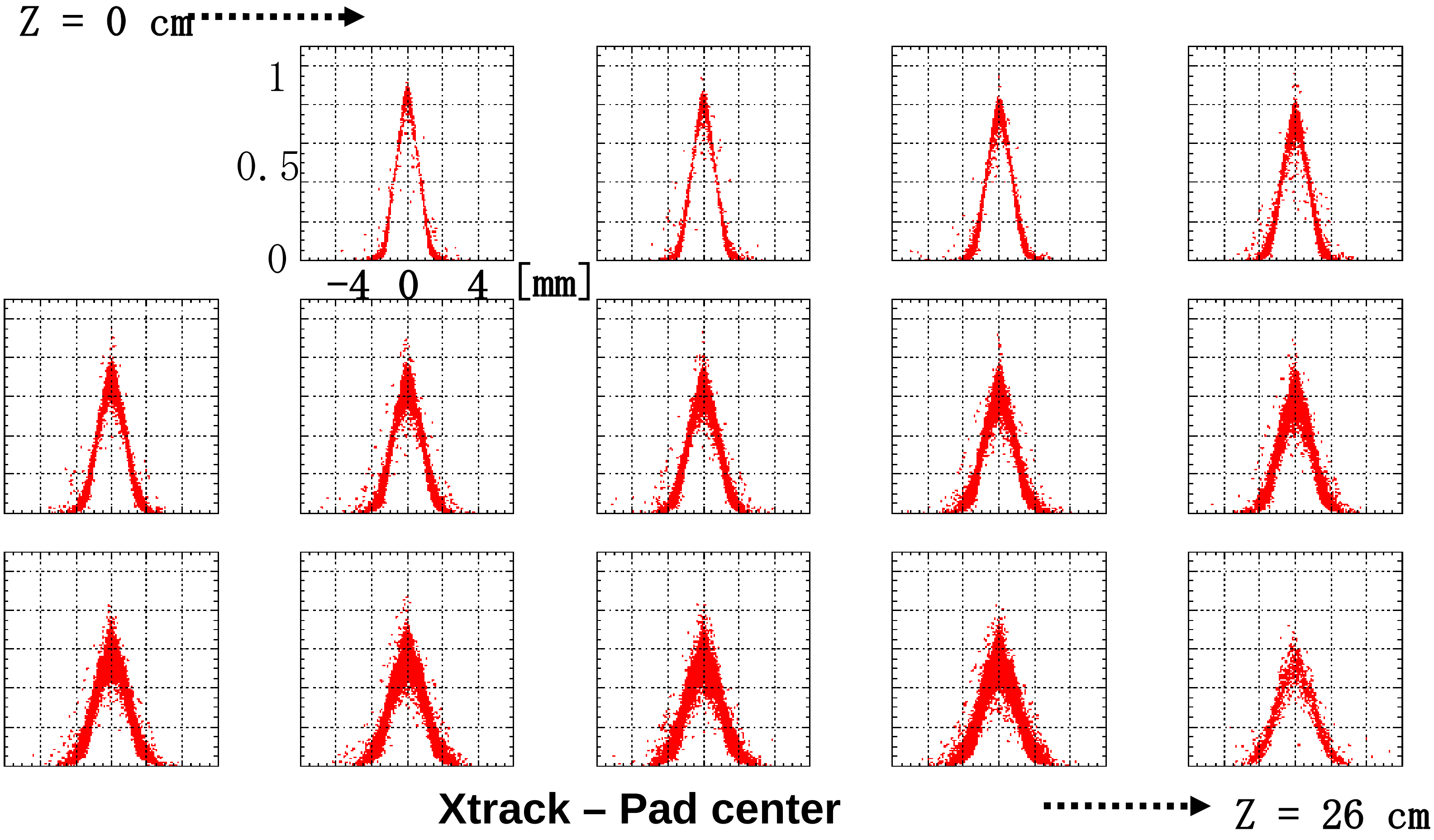
charge sensitive preamp. + shaper amp. (shaping time = 500 ns)

+ digitizer (time bucket = 80 nsec)

Examples of Experimental Data

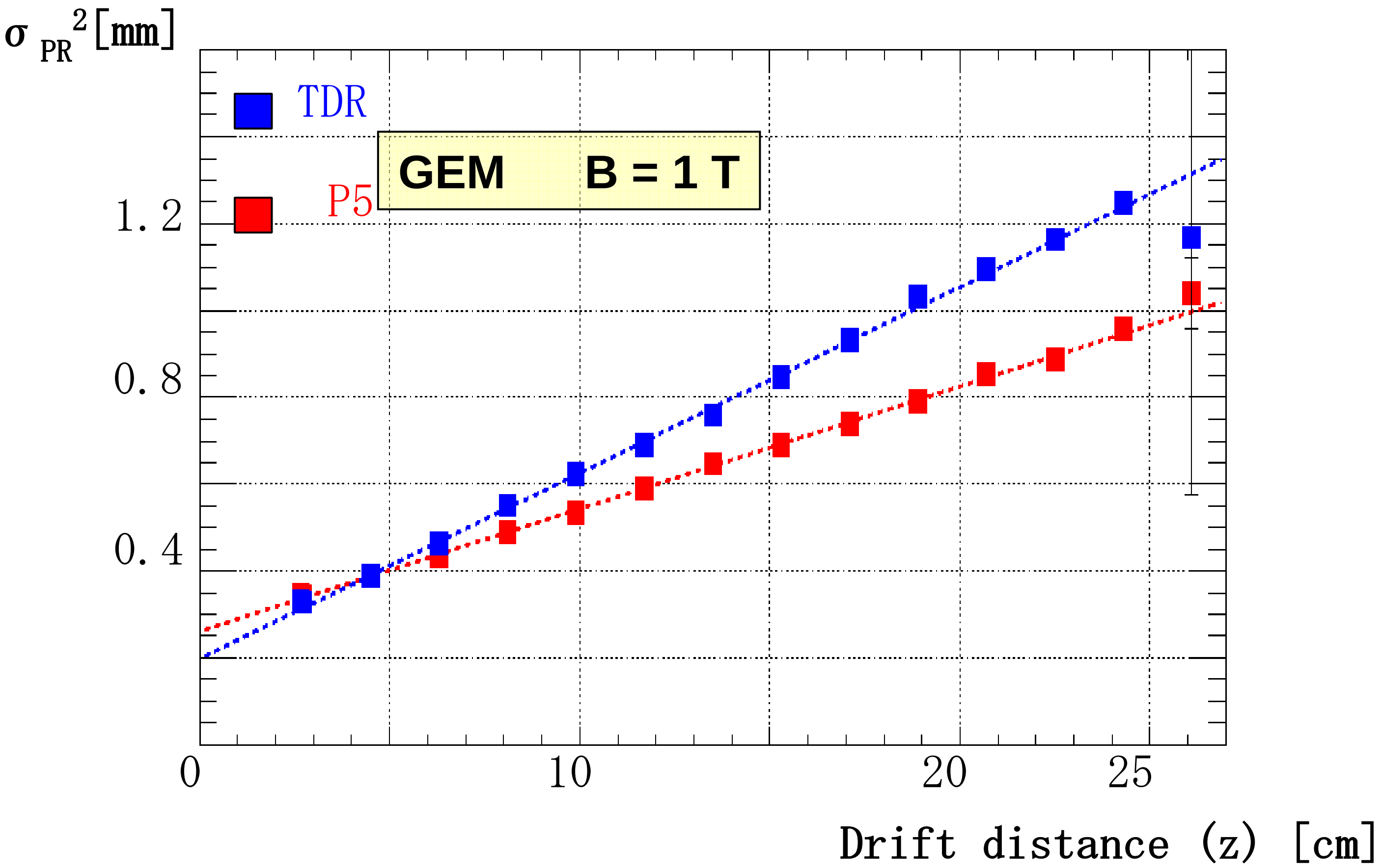
Pad responses for different drift distances

GEM Gas: P5, B = 1 T



Xtrack – Pad center

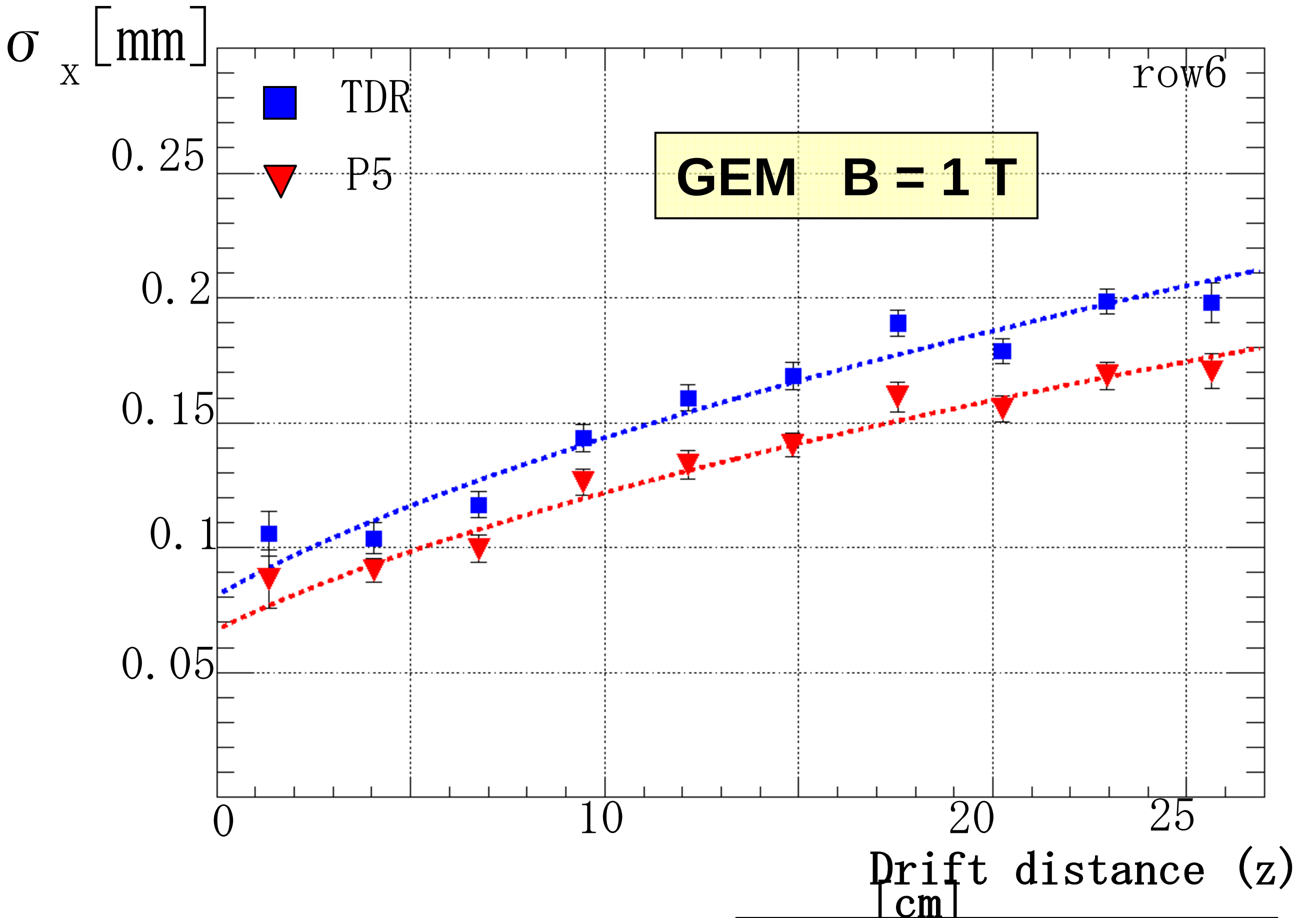
Pad response width vs. z



$$\sigma_{PR}^2 = \sigma_{PR0}^2 + D^2 z$$

	σ_{PR0} (μm)	D (μm/$\sqrt{\text{cm}}$)
TDR	443 ± 5	207 ± 1
P5	511 ± 2	168 ± 1

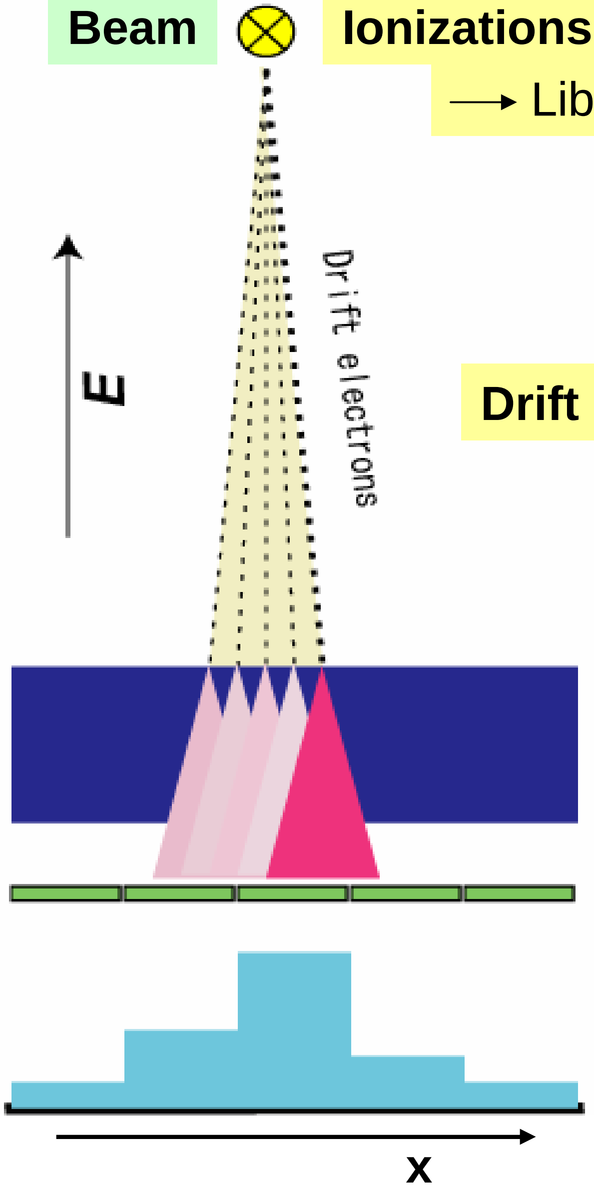
Spatial resolution vs. z



$$\sigma_X = \sqrt{\sigma_{X0}^2 + D^2 / N_{\mathrm{eff}}\ z}$$

	σ_{X0} (μm)	N_{eff}
TDR	81 ± 6	30 ± 2
P5	67 ± 6	27 ± 2

Track coordinate measurement



Beam

Ionizations

→ Liberation of Electrons

Drift Volume

Drift and Diffusion

Amplification Gap

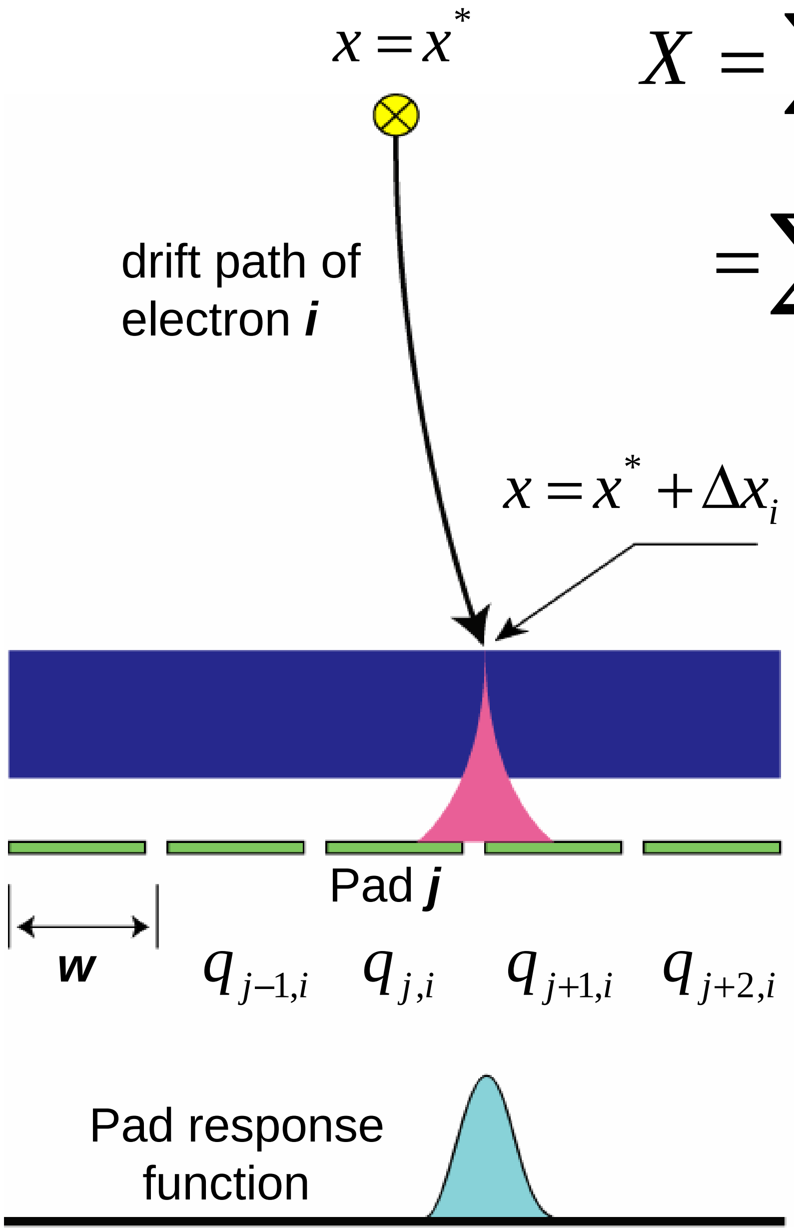
Amplification and further Diffusion

Readout Pads

Pad Response

→ **Coordinate**

Charge Centroid X



$$X = \sum_j (jw)\left(\sum_i q_{ji} / \sum_i \sum_j q_{ji}\right)$$

$$= \sum_i Q_i \sum_j (jw) F_j(x^* + \Delta x_i) / \sum_i Q_i \,,$$

where $Q_i = \sum_j q_{ji}$,

$$F_j(x^* + \Delta x_i) \equiv q_{ji} / Q_i$$

w **: pad pitch**

j **: pad #**

$q_{j,i}$ is the charge on pad *j* created by drift electron *i* .

Δx_i ***is the displacement due to lateral diffusion and its variance is given by*** $< \Delta x^2 > = D^2 z$ ***, where*** D ***is the diffusion constant and z is the drift distance.***

i runs through 1 to N, where N is the total number of drift electrons (not a constant).

Formulation of Spatial Resolution

for tracks perpendicular to the pad row

$$\sigma_X^2 = \int_{-1/2}^{+1/2} d\left(\frac{x^*}{w}\right) \left\{ [\mathrm{i}] + \frac{1}{N_{\mathrm{eff}}} [\mathrm{ii}] \right\} + [\mathrm{III}]$$

$$[\mathrm{i}] \equiv \left\{ \sum_j (jw) \left\langle F_j(x^* + \Delta x) \right\rangle - x^* \right\}^2$$

$$[\mathrm{ii}] \equiv \sum_{j,k} jkw^2 \left\langle F_j(x^* + \Delta x) F_k(x^* + \Delta x) \right\rangle - \left(\sum_j jw \left\langle F_j(x^* + \Delta x) \right\rangle \right)^2$$

$$[\mathrm{III}] \equiv \frac{\left\langle (\Delta q)^2 \right\rangle}{\left\langle Q \right\rangle^2} \left\langle \frac{1}{N^2} \right\rangle \sum_j (jw)^2$$

(Δq : electric noise charge on a pad

where $N_{\mathrm{eff}} \equiv \left\{ \left\langle \frac{1}{N} \right\rangle \frac{\left\langle Q^2 \right\rangle}{\left\langle Q \right\rangle^2} \right\}^{-1}$ **and**

$$\left\langle F_j(x^* + \Delta x) \right\rangle \equiv \int_{-\infty}^{+\infty} d(\Delta x) P_D F_j(x^* + \Delta x)$$

with $P_D \equiv \frac{1}{\sqrt{2\pi} D} \exp\left(-\frac{(\Delta x)^2}{2D^2} \right).$

The definition is similar for < Fj ·Fk > .

Remarks on the Formulation

$$F_j(x) \equiv \int_{jw-w/2}^{jw+w/2} f(\xi - x)\, d\xi$$

with $f(x)$ being the normalized pad response function.

Therefore *Fj* can be evaluated once the pad response function is defined.

$$N_{\mathrm{eff}} \equiv \left\{ \left\langle \frac{1}{N} \right\rangle \frac{\langle Q^2 \rangle}{\langle Q \rangle^2} \right\}^{-1} \equiv \frac{\langle N \rangle}{R},$$

where *R* is defined as $R \equiv (1+K) < N >< N^{-1} >$

with $K \equiv \sigma_Q^2 / < Q >^2,$

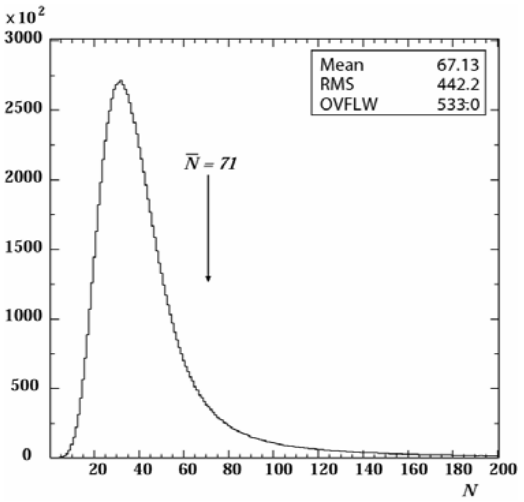
the relative variance of avalanche fluctuation for a single drift electron.

$< N >< N^{-1} >$ **is greater than 1 because of asymmetric distribution of *N*.**

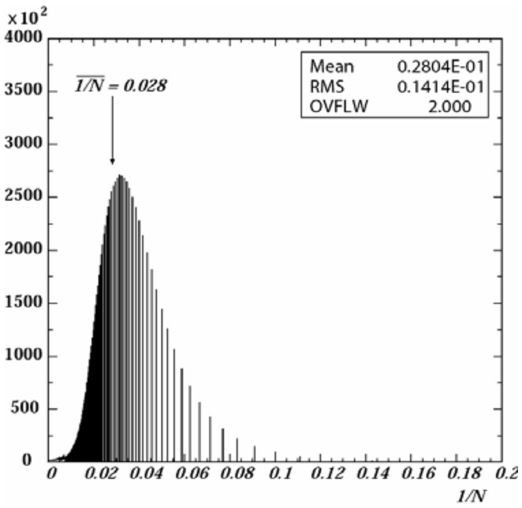
Therefore the effective number of electrons is smaller than the average number of drift electrons.

Remarks (cont’d)

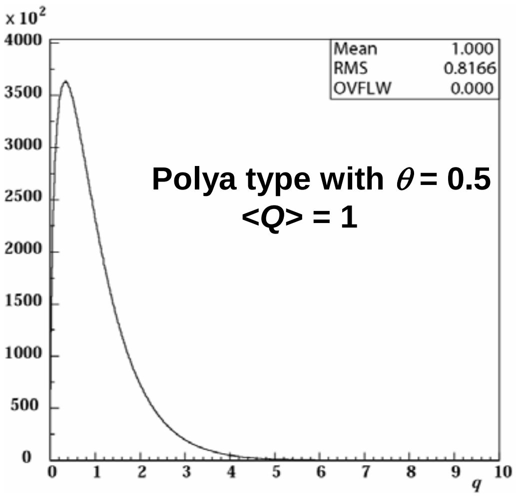
An example of estimation of *N*eff
for 4 GeV/c pions and pad row pitch of 6.3 mm
in pure argon



Distribution of *N*
(<*N*> = 71)



Distribution of 1/*N*
(<1/*N*> = 0.028)



Polya type with $\theta = 0.5$
<*Q*> = 1

Distribution of *Q*
(*K* = 0.67)

$$R \equiv (1+K) < N > < N^{-1} > \approx (1+0.67) \times 71 \times 0.028 \approx 3.32$$

$$N_{\text{eff}} = \frac{\langle N \rangle}{R} \approx 21$$

Origin and characteristic of each term

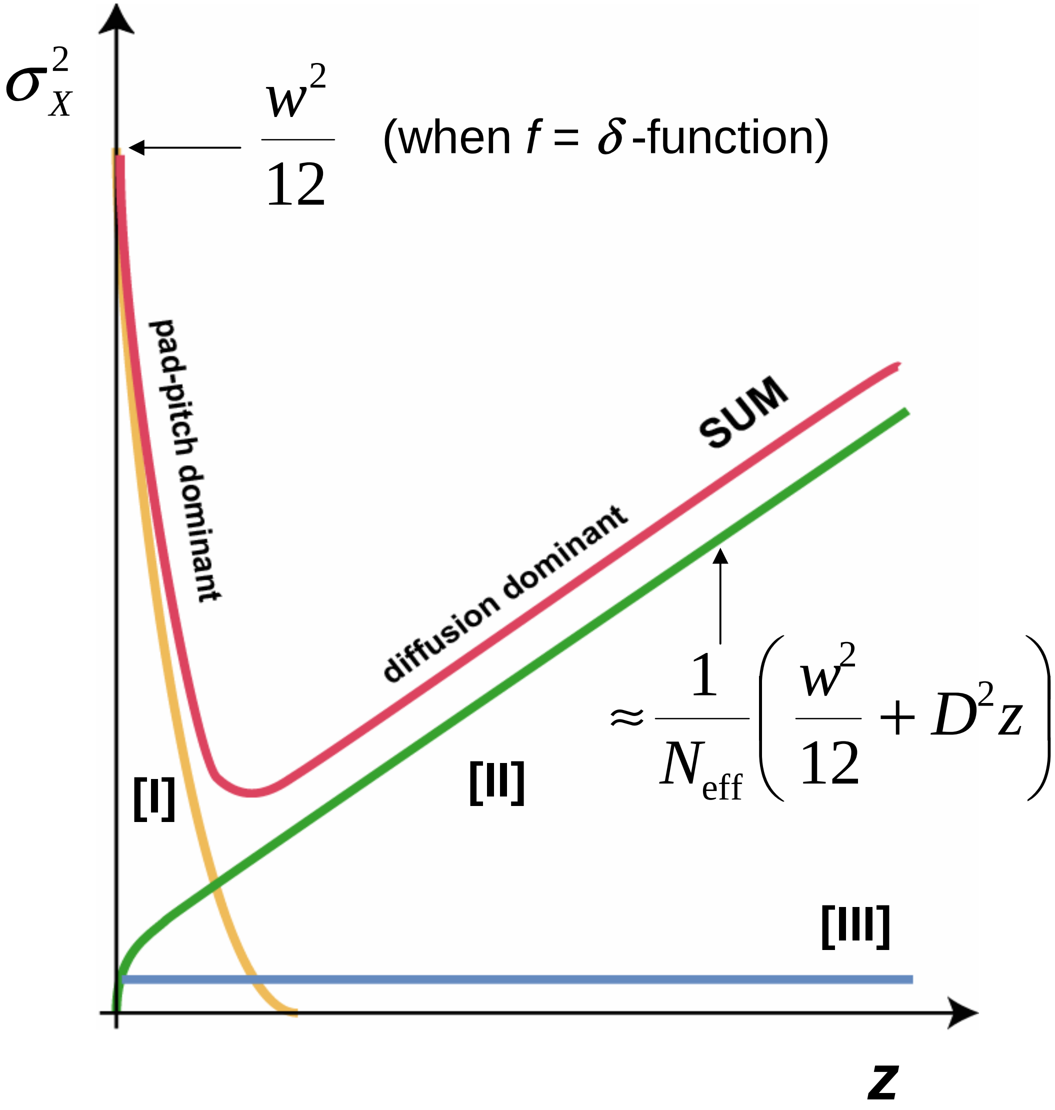
[I] Finite pad pitch ⟶ systematic biases due to charge centroid method.
Rapidly decreases with drift distance (*z*) because of diffusion. *N* independent. $w^2/12$ at $z=0$ when $f=\delta$.

This term can be reduced by calibration if the signal charge is shared by two or more pads.
In reality, however, electronic noise significantly degrades the resolution when the charge sharing among the pads is not sufficient.

[II] Diffusion, gas-gain fluctuation, finite pad pitch combined.
Gradually increases with drift distance, asymptotically $1/N_{\mathrm{eff}}\cdot\left(w^2/12+D^2z\right)$.

[III] Random electronic noise. *z* independent.

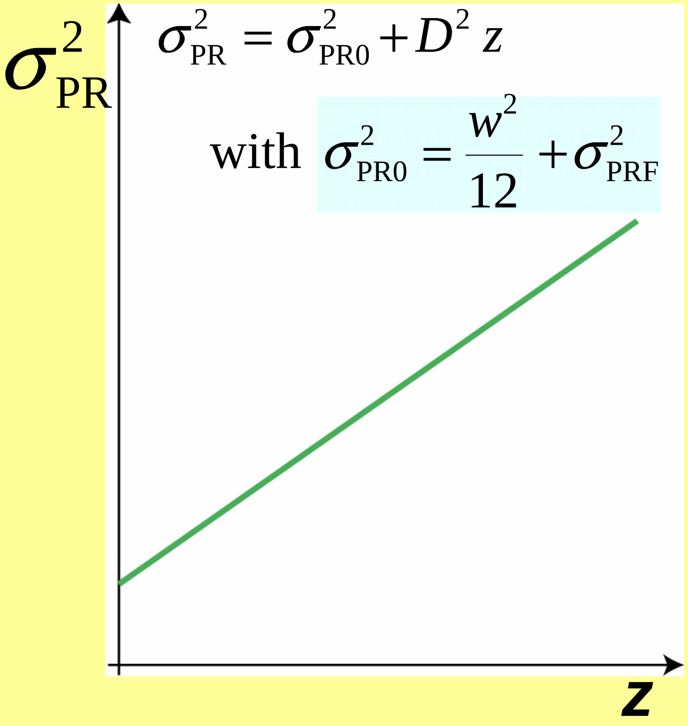
Illustration of each contribution



$\frac{w^2}{12}$ (when $f = \delta$-function)

$$\approx \frac{1}{N_{\mathrm{eff}}}\left(\frac{w^2}{12} + D^2 z\right)$$

Pad Response



$$\sigma_{\mathrm{PR}}^2 = \sigma_{\mathrm{PR0}}^2 + D^2 z$$

with $\sigma_{\mathrm{PR0}}^2 = \frac{w^2}{12} + \sigma_{\mathrm{PRF}}^2$

Brief Summary of Formulation

If *w*, *D*, *f* and *Neff* are known σ_X can readily be calculated for given *z*.

- ***w*: known**

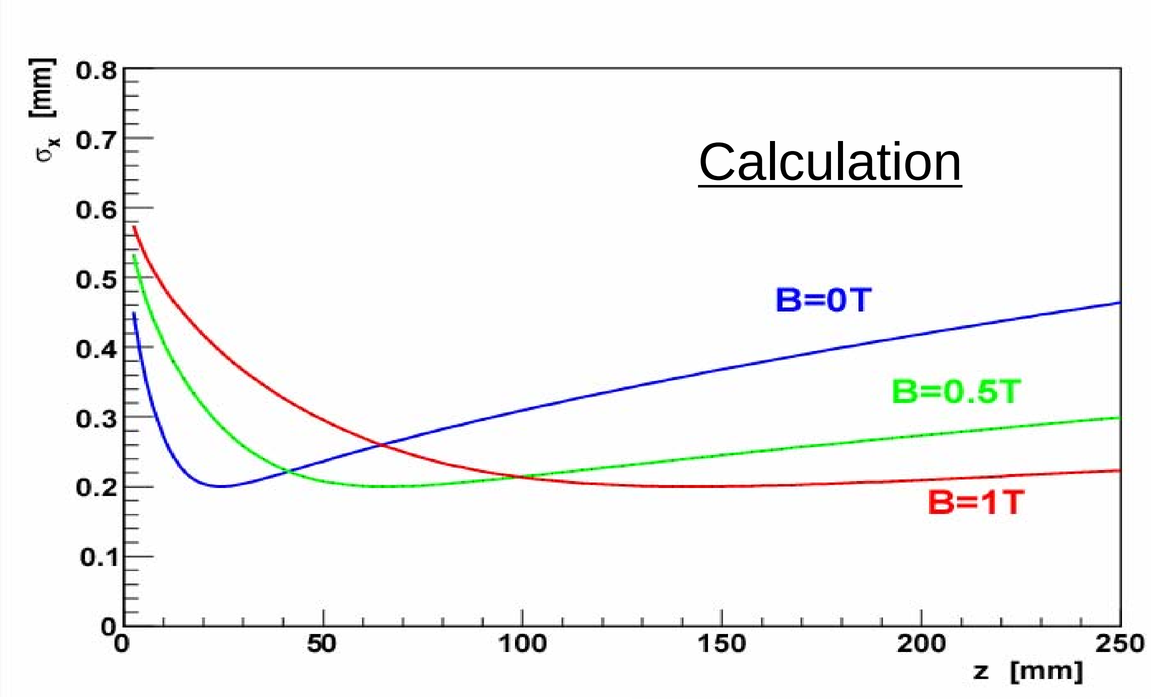
- ***D*: measured**: determined from z-dependence of pad-response width
  (or given by Monte-Carlo simulation)

- ***Neff*: measured**: determined from ***D*** and z-dependence of spatial resolution
  (or estimated with assumptions on ionization statistics and avalanche fluctuation)

- ***f* (pad response function): not known** (Monte-Carlo simulation?)
  ⟶ δ- function is assumed for ***f***.
  (expected to be a good approximation in the case of microMEGAS)

- electronic noise (σ_{NOISE}): measurable and different from pad to pad
  ⟶ considered here as a constant term independent of ***z***

Examples of Calculated Resolution



w = 2.3 mm

D = 469, 285 and 193 $\mu\mathrm{m}/\sqrt{\mathrm{cm}}$
respectively for
B = 0, 0.5, and1.0 T
(gas: Ar-isobutane (5%))

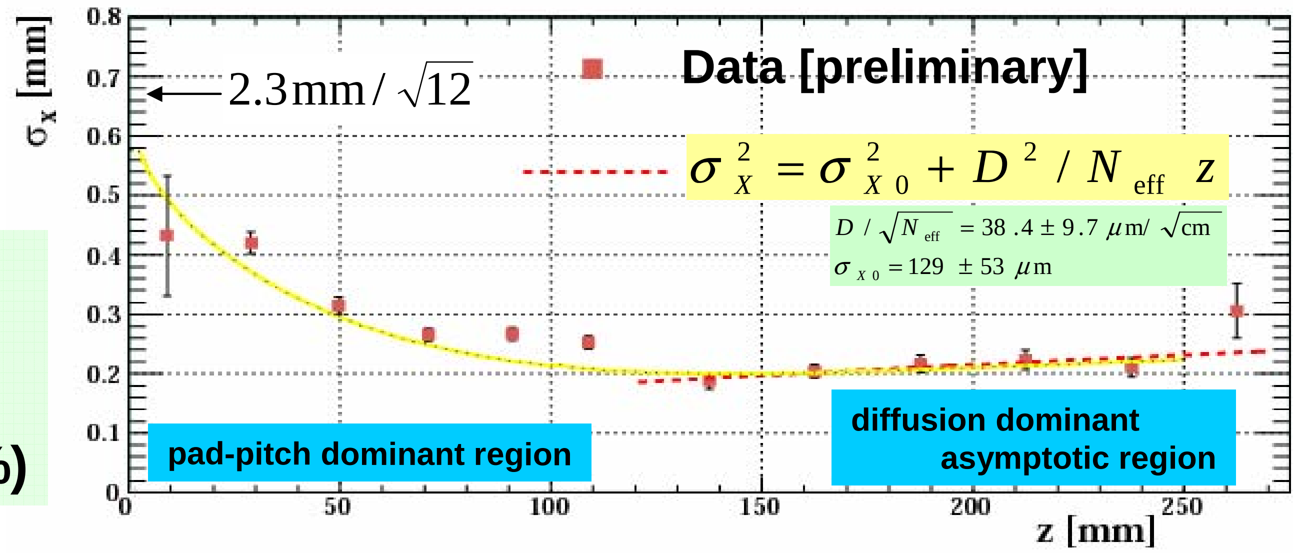
Neff = 27.5

f : δ function

Electronic noise: absent

Comparison with the real data

Data: MicroMEGAS
B = 1 T
ϕ = 0°
Gas: Ar-isobutane (5%)



Asymptotic behavior at long drift distances

Expectation vs. Data [Preliminary]

Pad Response (B = 1 T)

PRF dominant

	MWPC	GEM		MicroMEGAS
Gas	TDR	TDR	P5	Ar-isobutane (5%)
$\sigma_{\mathrm{PR0}}\,(\mu\mathrm{m})$	1390	443±5	511±2	781±79
$w/\sqrt{12}\,(\mu\mathrm{m})$	663 (w = 2.3 mm)	367 (w = 1.27 mm)		663 (w = 2.3 mm)
$D\;(\mu\mathrm{m}/\sqrt{\mathrm{cm}})$	220	207±1	168±1	198±15
D [MAGBOLTZ]	200	200	166	193

$$\sigma_{\mathrm{PR}}^2 \approx \sigma_{\mathrm{PR0}}^2 + D^2 z \quad \text{with} \quad \sigma_{\mathrm{PR0}}^2 = w^2/12 + \sigma_{\mathrm{PRF}}^2$$

Spatial Resolution (B = 1 T)

small S/N ratio

	MWPC	GEM		MicroMEGAS
Gas	TDR	TDR	P5	Ar-isobutane (5%)
$\sigma_{\mathrm{X0}}\,(\mu\mathrm{m})$	220	81±6	67±6	129±53
$\frac{1}{\sqrt{N_{\mathrm{eff}}}}\frac{w}{\sqrt{12}}\,(\mu\mathrm{m})$	135	67	71	128
$\frac{D}{\sqrt{N_{\mathrm{eff}}}}\;(\mu\mathrm{m}/\sqrt{\mathrm{cm}})$	45	38±1	32±1	38±10
N_{eff}	24	30±2	27±2	27±14

$$\sigma_{\mathrm{X}}^2 \approx \sigma_{\mathrm{X0}}^2 + \frac{1}{N_{\mathrm{eff}}} D^2 z \quad \text{with} \quad \sigma_{\mathrm{X0}}^2 = \frac{1}{N_{\mathrm{eff}}}\frac{w^2}{12} + \sigma_{\mathrm{NOISE}}^2$$

Summary of Comparison (at long drift distances)

- **σ_{PR0} is in reasonable agreement with the expectation ($w/\sqrt{12}$) if the contribution of σ_{PRF} is taken into account.**

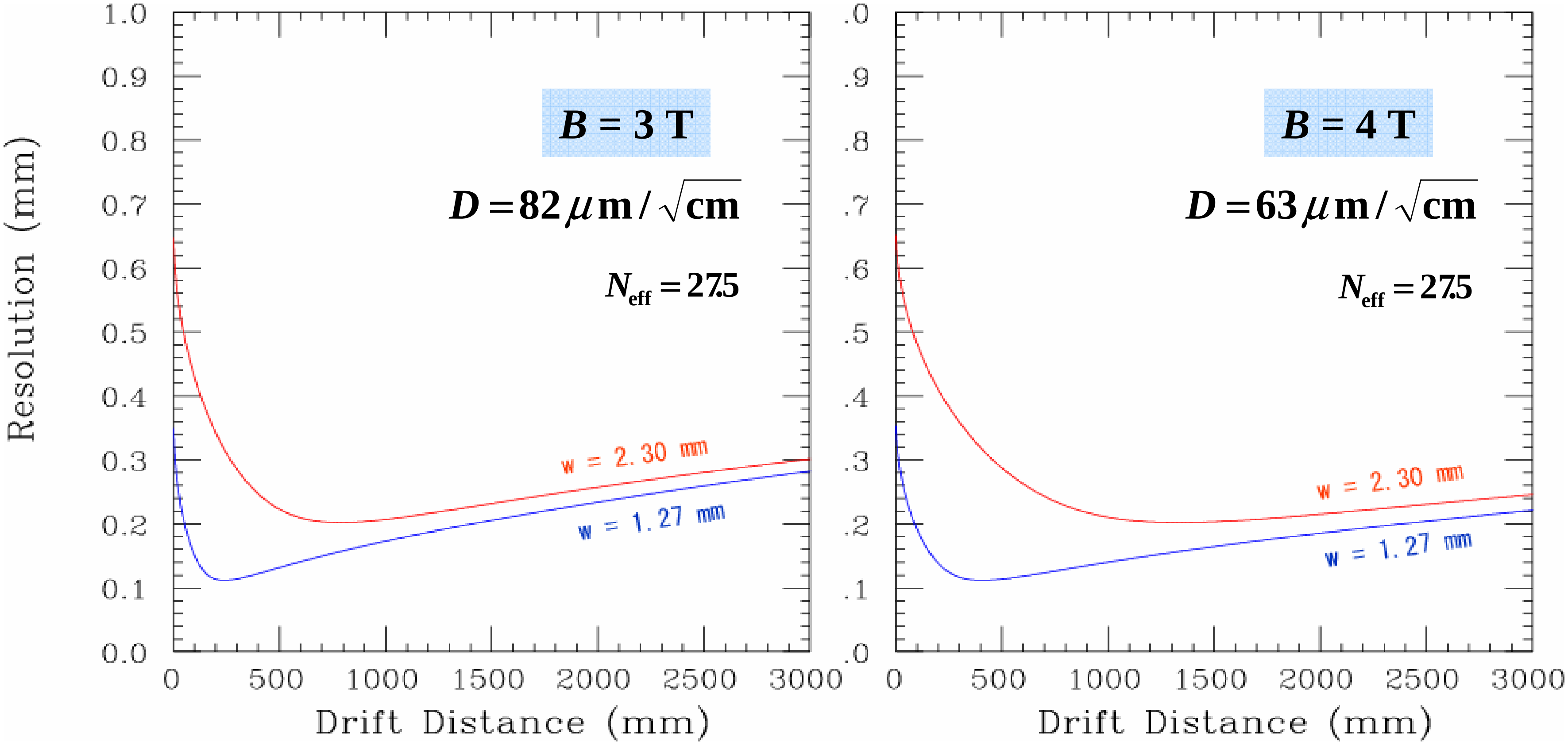
- **σ_{X0} is in reasonable agreement with the expectation ($w/\sqrt{12N_{\mathrm{eff}}}$) except for the case where the contribution of electronic noise is significant.**

- **The values of *D* (diffusion constant) are comparable to those given by the simulation (MAGBOLTZ).**

- **N_{eff} is significantly smaller than the average number of drift electrons.**

Calculated Resolution of LC TPC

for tracks perpendicular to the pad row ($\phi = 0^\circ$)



Gas: Ar – isobutane (5%)

PRF: δ - function

Charge centroid method (without “bias” correction)

Under a stronger magnetic field

It is important to reduce the pad-pitch dominant region in the Linear Collider TPC.

Basic strategy: Charge sharing among two or more pads → Bias correction

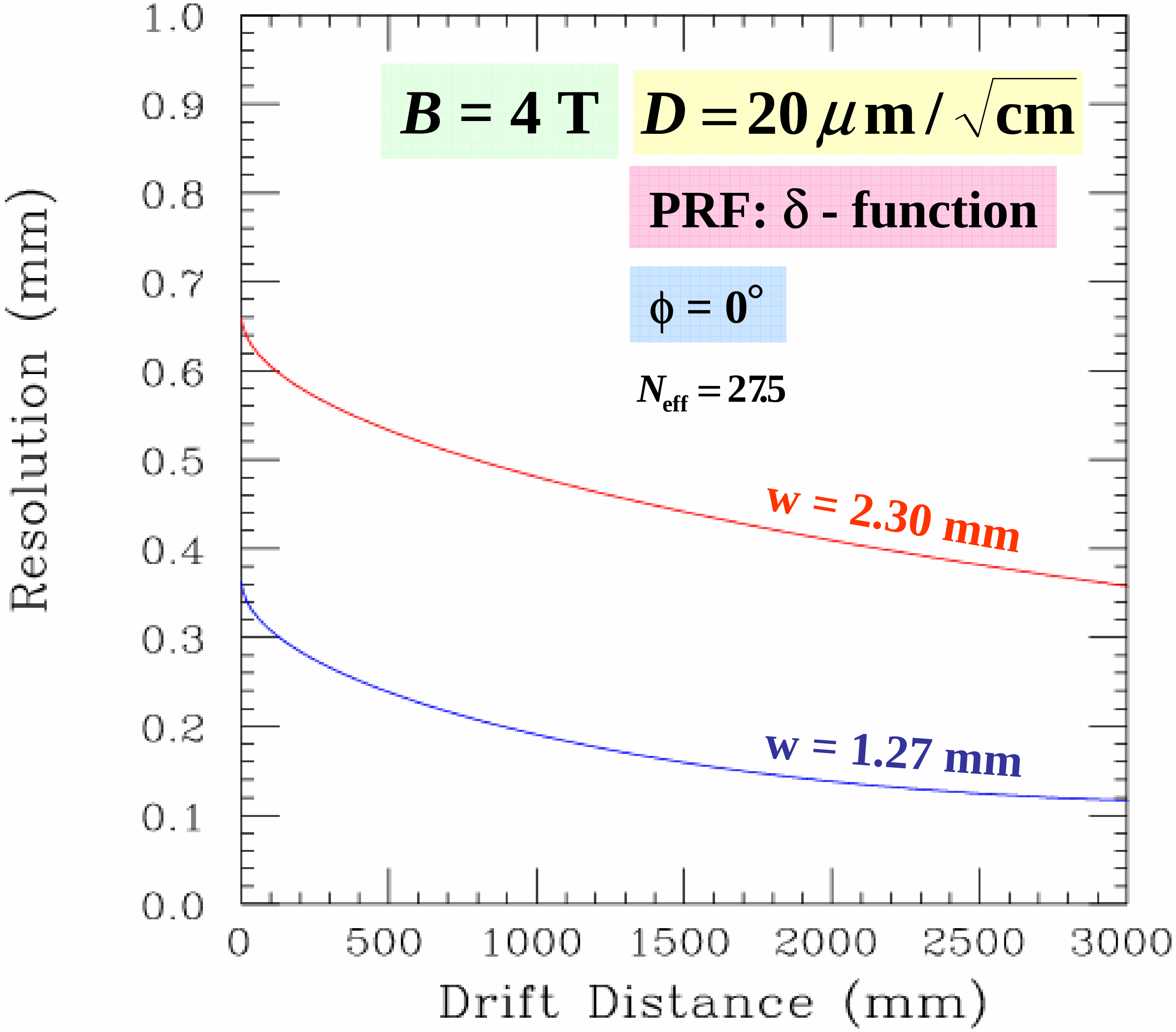
⇒ **Smaller pad pitch**
with a larger number of readout channels

⇒ Defocusing of multiplied electrons
in the detection gap (GEM) [***stochastic*** PRF]

⇒ **Use of resistive anode technique**
with a moderate number of readout channels
(GEM or MicroMEGAS) **[*static* PRF]**
(→ Next talk by Madhu)

* **PIXEL Readout [Digital TPC] (→ Tomorrow's talk by Paul)**

What if we use Ar-CF4 (3%)?



$B = 4\ \mathrm{T}$

$D = 20\,\mu\mathrm{m}/\sqrt{\mathrm{cm}}$

PRF: δ - function

$\phi = 0^\circ$

$N_{\mathrm{eff}} = 27.5$

w = 2.30 mm

w = 1.27 mm

Summary

- Spatial resolution is understood in terms of pad pitch, diffusion, PRF, and the effective number of electrons (Neff).
- Expected resolution can be estimated by a numerical calculation (NOT a Monte-Carlo) for given geometry, gas mixture and PRF if the relevant parameters are known.
- The calculation is based on a simple formula, easy to code, and fast, though it is available only to the tracks perpendicular to the pad row.
- It is essential to make pad pitch small, *physically* or *effectively*, in order to minimize (eliminate) the pad-pitch dominant volume in the TPC.